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MODELLING AND SIMULATION OF SVPWM INVERTER FED PERMANENT MAGNET BRUSHLESS DC MOTOR DRIVE

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ABSTRACT: Variable speed drives with Pulse Width Modulation are increasingly applied in many new industrial applications for more efficient performance. Recently, developments in power electronics and semiconductor technology have lead to widespread use of power electronic converters in the power electronic systems. A number of Pulse width modulation (PWM) schemes are used to obtain variable voltage and frequency supply from a three-phase voltage source inverter. Among the different PWM techniques proposed for voltage fed inverters, the sinusoidal PWM technique has been popularly accepted. But there is an increasing trend of using space vector PWM (SVPWM) because of their easier digital realization, reduced harmonics, reduced switching losses and better dc bus utilization. This paper focuses on step by step development of SVPWM implemented on a PMBLDC motor. Simulation results are obtained using MATLAB/Simulink environment for effectiveness of the study.

Keywords: Permanent Magnet Brushless DC Motor, Pulse width modulation (PWM), Sinusoidal PWM, Space Vector PWM, Voltage Source Inverter.

I.INTRODUCTION

The inverters are used to converts dc power into ac power at desired output voltage and frequency. The waveform of the output voltage depends on the switching states of the switches used in the inverter. Major limitations and requirements of inverters are harmonic contents, the switching frequency, and the best utilization of dc link voltage. Pulse width modulation (PWM) inverters are studied extensively during the past decades. In this method, a fixed dc input voltage is given to the inverter and a controlled ac output voltage is obtained by adjusting the on and off periods of the inverter components. The most popular PWM techniques are the sinusoidal PWM and space Vector PWM. With the development of DSPs, space-vector modulation (SVM) has become one of the most important PWM methods for three-phase voltage source inverters. In this technique, Space-vector concept is used to compute the duty cycle of the switches. It is simply the digital implementation of PWM modulators. Most advanced features of SVM are easy digital implementation and wide linear modulation range for output line-to-line voltages.

II. SPACE VECTOR PWM

The Space Vector Pulse Width Modulation (SVPWM) refers to a special switching sequence of the upper three power devices of a three-phase voltage source inverters (VSI) used in application such as AC induction and permanent magnet synchronous motor drives.It is a more sophisticated technique for generating sine wave that provides a higher voltage to the motor with lower total harmonic distortion. Space Vector PWM (SVPWM) method is an advanced; computation intensive PWM method and possibly the best techniques for variable frequency drive application. In SVPWM technique, instead of using a separate modulator for each of the three phases, the complex reference voltage vector is processed as a whole. Therefore, the interaction between the three motor phases is considered. SVPWM generates less harmonic distortion in the output voltages and currents in the windings of the motor load and provides a more efficient use of the DC supply voltage in comparison with sinusoidal modulation techniques. Since SVPWM provides a constant switching frequency; the switching frequency can be adjusted easily. Although SVPWM is more complicated than sinusoidal PWM, it may be implemented easily with modern DSP based control systems.

A. Space Vector

Consider three phase waveforms which are displaced by 120°,

$$V_a = V_m \sin\omega t$$
$$V_b = V_m \sin(\omega t-120°)$$

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$$V_c = V_m \sin(\omega t+120°) \qquad (1)$$

These three vectors can be represented by a one vector which is known as space vector. Space vector is defined as,

$$V_s = V_a + V_b\, e^{\frac{j2\pi}{3}} + V_c\, e^{\frac{-j2\pi}{3}} \qquad (2)$$

$$\therefore \qquad \overline{V}_s = \frac{3}{2} V_m \,[\sin \omega t - j \cos \omega t\,] \qquad (3)$$

i.e, $\overline{V}_s$ is vector having magnitude of $\frac{3}{2} V_m$ and rotates in space at ω rad/sec as shown in Figure 1.

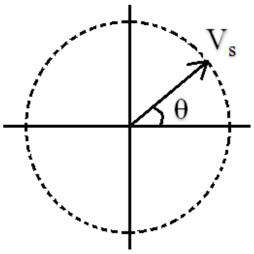

Fig.1: Rotating Space Vector

This vector can be represented in two dimensional space by simply resolving abc in to dq axis.

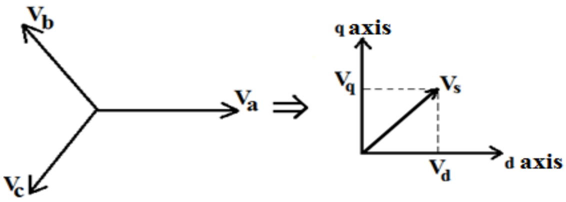

Fig.2: abc to dq transformation

Therefore space vector can also be written as

$$V_s = V_d + jV_q$$

$$\theta = \tan^{-1}\left(\frac{V_q}{V_d}\right) \qquad (4)$$

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad (5)$$

B. Principle of Space Vector PWM

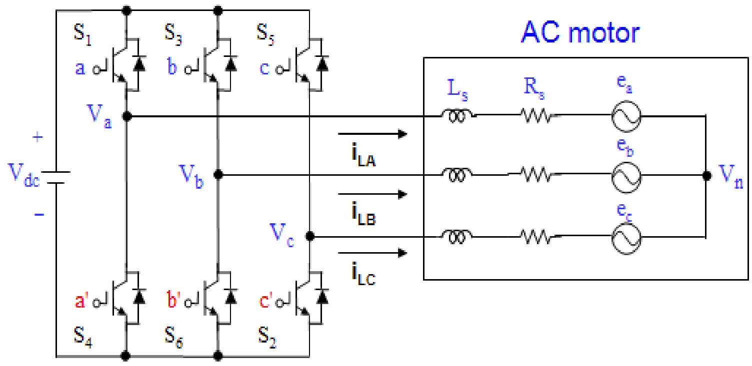

Fig.3: Three-phase voltage source PWM Inverter

SVPWM aims to generate a voltage vector that is close to the reference circle through the various switching modes of inverter. Figure 3 is the typical diagram of a three-phase voltage source inverter model. S1 to S6 are the six power switches that shape the output, which are controlled by the switching variables a, a’, b, b’, c and c’. When an upper transistor is switched ON, i.e., when a, b or c is 1, the corresponding lower transistor is switched OFF, i.e., the corresponding a’, b’ or c’ is 0. Therefore, the ON and OFF states of the upper transistors S1, S3 and S5 can be used to determine the output voltage. Hence there are 8 possible switch states, i.e.,(0,0,0), (0,0,1), (0,1,0), (0,1,1), (1,0,0), (1,0,1), (1,1,0), (1,1,1). The inverter has six states when a voltage is applied to the motor and two states when the motor is shorted through the upper or lower transistors resulting in zero volts being applied to the motor.

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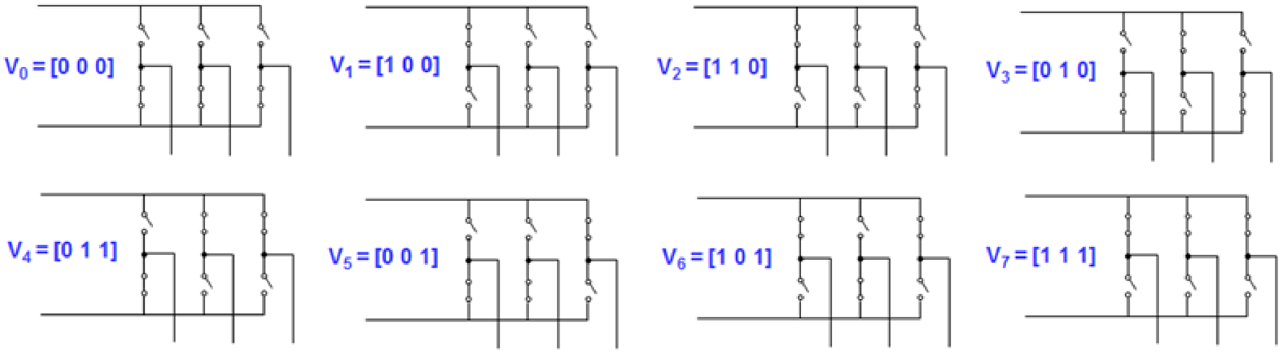

Fig.4: Inverter Voltage Vectors (V_0 to V_7)

Consider an inverter feeding a star connected load and center point of the dc link is take as reference point as shown in Figure 5,

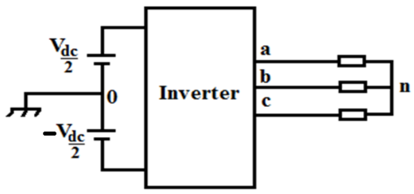

Fig.5: Inverter feeding a star connected load

The potential of point a, point b & point c with respect to the center point of the dc link is known if the conducting states of the switches are known. When upper switch is 'ON', the potential of a, b &c is $\frac{V_{dc}}{2}$ & when lower switch is 'ON', the potential of a, b &c is $-\frac{V_{dc}}{2}$.

$$V_{a0} = V_{an} + V_{n0}$$
$$V_{b0} = V_{bn} + V_{n0}$$
$$V_{c0} = V_{cn} + V_{n0} \qquad (6)$$

& $$V_{n0} = \frac{1}{3}\left[V_{a0} + V_{b0} + V_{c0}\right] \qquad (7)$$

$$\therefore \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} V_{a0} \\ V_{b0} \\ V_{c0} \end{bmatrix} \qquad (8)$$

Consider the switching states, (0,0,0) & (1,1,1)

$$V_{an} = V_{bn} = V_{cn} = 0;$$

Hence, $$V_d = V_q = 0$$

Therefore,

$$V_s = 0\angle 0° \qquad (9)$$

Now consider the switching state (1,0,0),

$$V_{a0} = \frac{V_{dc}}{2},\ V_{b0} = V_{c0} = -\frac{V_{dc}}{2}$$

$$V_{an} = \frac{2}{3}V_{dc},\ V_{bn} = V_{cn} = -\frac{1}{3}V_{dc}$$

Hence, $$V_d = \frac{3}{2}V_{an} = V_{dc} \ \ \&\ \ V_q = 0$$

Therefore, $$V_s = V_{dc}\angle 0° \qquad (10)$$

Since (0,1,1) is the complementary of (1,0,0);

For (0,1,1),

$$V_s = V_{dc}\angle 180° \qquad (11)$$

Similarly derive the magnitude and angle of space vector for all possible switching states.

They are,

- For (0,0,0) : $V_s = 0\angle 0°$ $\rightarrow V_0$
- For (1,0,0) : $V_s = V_{dc}\angle 0°$ $\rightarrow V_1$
- For (1,1,0) : $V_s = V_{dc}\angle 60°$ $\rightarrow V_2$

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- For (0,1,0) : $V_s = V_{dc} \angle 120°$ $\rightarrow V_3$
- For (0,1,1) : $V_s = V_{dc} \angle 180°$ $\rightarrow V_4$
- For (0,0,1) : $V_s = V_{dc} \angle 240°$ $\rightarrow V_5$
- For (1,0,1) : $V_s = V_{dc} \angle 300°$ $\rightarrow V_6$
- For (1,1,1) : $V_s = 0\angle 0°$ $\rightarrow V_7$

There are 6 non-zero vectors (V_1 to V_6) and 2 zero vectors (V_0 & V_7). Table 1 summarizes switching vectors along with the corresponding line to neutral voltage and line to line voltages applied to the motor.

Table 1: Switching vectors, phase voltages and output line to line voltages

Voltage Vectors	Switching Vectors			Line to neutral voltage			Line to line voltage		
	a	b	c	V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_{ca}
V_0	0	0	0	0	0	0	0	0	0
V_1	1	0	0	2/3	-1/3	-1/3	1	0	-1
V_2	1	1	0	1/3	1/3	-2/3	0	1	-1
V_3	0	1	0	-1/3	2/3	-1/3	-1	1	0
V_4	0	1	1	-2/3	1/3	1/3	-1	0	1
V_5	0	0	1	-1/3	-1/3	2/3	0	-1	1
V_6	1	0	1	1/3	-2/3	1/3	1	-1	0
V_7	1	1	1	0	0	0	0	0	0

(Note that the respective voltage should be multiplied by V_{dc})

While plotting 8 voltage vectors in complex plane, the non-zero vectors form the axes of a hexagon as shown in Figure 6.The angle between any adjacent two non-zero vectors is 60 electrical degrees. The zero vectors (or null vectors) are at the origin and apply a zero voltage vector to the motor. If the phase voltages are sinusoidal, locus of the 'V_s' is circle. The maximum value of V_s for which locus is circle is the radius of the inscribing circle, i.e, $\frac{\sqrt{3}}{2} V_{dc}$.

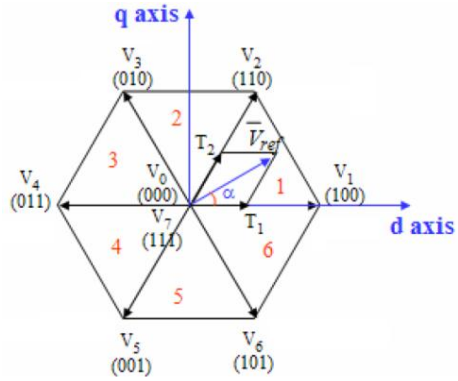

Fig.6: Basic switching vectors and sectors

III.REALIZATION OF SPACE VECTOR PWM

The space vector PWM is realized based on the following steps:

A. Step 1: Determine V_d, V_q, V_{ref}, and angle (α)

From Equation 5, the V_d, V_q, V_{ref}, and angle (α) can be determined as follows:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix}$$

$$|\overline{V}_{ref}| = \sqrt{V_d{}^2 + V_q{}^2}$$

$$\propto = \tan^{-1}\left(\frac{V_q}{V_d}\right) \qquad (12)$$

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B. Step 2: Determine time duration T_1, T_2, T_0

In space vector PWM technique, the required space vector is synthesized by two adjacent vectors and null vector.

- Switching time duration at Sector 1

From Figure 7, the switching time duration can be calculated as follows:

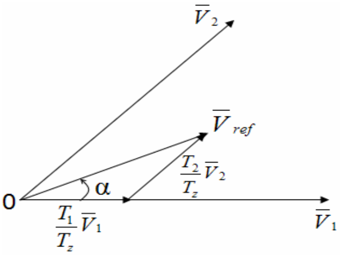

Fig.7: Reference vector as a combination of adjacent vectors at sector1

According to volt-sec balance principle,

$$\int_0^{T_Z} \overline{V}_{ref}\,dt = \int_0^{T_1} \overline{V}_1 dt + \int_{T1}^{T_1+T_2} \overline{V}_2 dt + \int_{T_1+T_2}^{T_Z} \overline{V}_0 dt$$

$$\therefore T_Z \cdot \overline{V}_{ref} = (T_1 \cdot \overline{V}_1 + T_2 \cdot \overline{V}_2)$$

$$T_Z \cdot \left|\overline{V}_{ref}\right| \cdot \begin{bmatrix} \cos(\alpha) \\ \sin(\alpha) \end{bmatrix} = T_1 \cdot \overline{V}_1 \cdot \begin{bmatrix} 1 \\ 0 \end{bmatrix} + T_2 \cdot \overline{V}_2 \cdot \begin{bmatrix} \cos(\pi/3) \\ \sin(\pi/3) \end{bmatrix}$$

$$\therefore T_1 = T_Z \cdot \frac{\left|\overline{V}_{ref}\right|}{V_{dc}} \cdot \frac{\sin(\pi/3-\alpha)}{\sin(\pi/3)}$$

$$\therefore T_2 = T_Z \cdot \frac{\left|\overline{V}_{ref}\right|}{V_{dc}} \cdot \frac{\sin(\alpha)}{\sin(\pi/3)} \qquad \text{Where } 0 \le \alpha \le 60^\circ,\ T_Z = \frac{T_S}{2}\ \&\ T_S = \frac{1}{f_S} \tag{13}$$

$$\therefore T_0 = T_Z - (T_1 + T_2)$$

T_1 is the time for which $\overline{V}_1$ is applied
T_2 is the time for which $\overline{V}_2$ is applied
T_0 is the time for which null vector is applied
T_s is the sampling time

Similarly switching time duration at any sector can be calculated.

C. Step 3: Determine the switching time of each transistor (S1 to S6)

Figure 8 shows Space Vector PWM switching patterns at each sector.

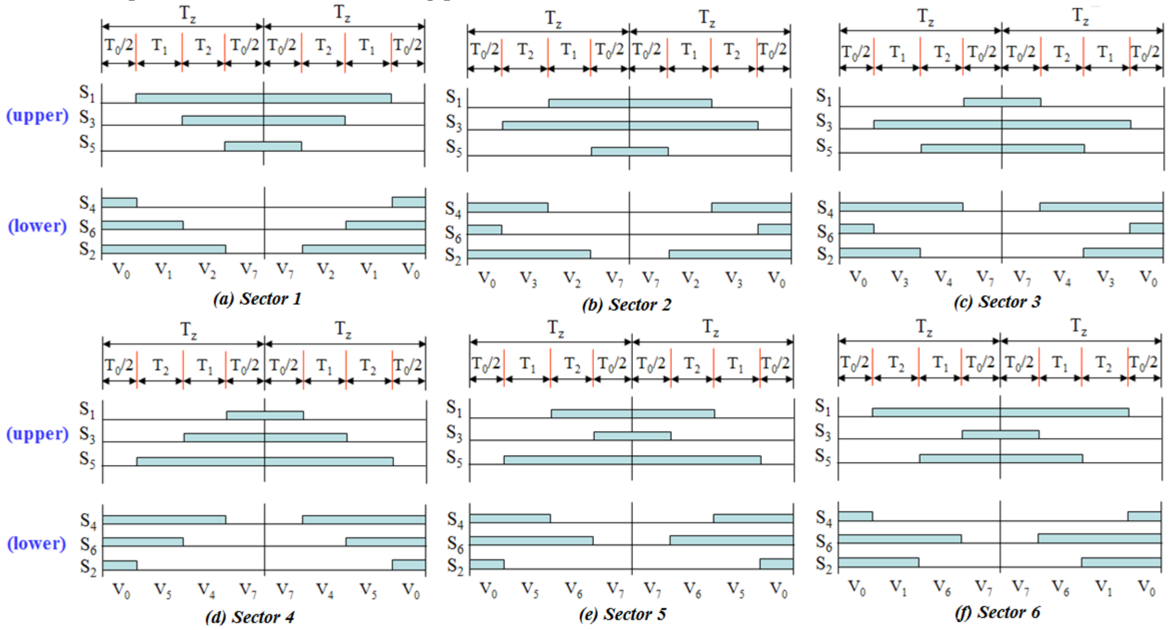

Fig.8: Space Vector PWM switching patterns at each sector

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Based on Figure 8, the switching time at each sector is summarized in Table 2, and it will be built in simulink model to implement SVPWM.

Table 2: Switching Time Calculation at each Sector

Sector	Upper Switches (S_1, S_3, S_5)	Lower Switches (S_4, S_6, S_2)
1	$S_1 = T_1 + T_2 + T_0/2$ $S_3 = T_2 + T_0/2$ $S_5 = T_0/2$	$S_4 = T_0/2$ $S_6 = T_1 + T_0/2$ $S_2 = T_1+T_2+T_0/2$
2	$S_1 = T_1 + T_0/2$ $S_3 = T_1 + T_2 + T_0/2$ $S_5 = T_0/2$	$S_4 = T_2 + T_0/2$ $S_6 = T_0/2$ $S_2 = T_1+T_2+T_0/2$
3	$S_1 = T_0/2$ $S_3 = T_1 + T_2 + T_0/2$ $S_5 = T_2 + T_0/2$	$S_4 = T_1+T_2+T_0/2$ $S_6 = T_0/2$ $S_2 = T_1 + T_0/2$
4	$S_1 = T_0/2$ $S_3 = T_1 + T_0/2$ $S_5 = T_1 + T_2 + T_0/2$	$S_4 = T_1+T_2+T_0/2$ $S_6 = T_2 + T_0/2$ $S_2 = T_0/2$
5	$S_1 = T_2 + T_0/2$ $S_3 = T_0/2$ $S_5 = T_1 + T_2 + T_0/2$	$S_4 = T_1 + T_0/2$ $S_6 = T_1+T_2+T_0/2$ $S_2 = T_0/2$
6	$S_1 = T_1 + T_2 + T_0/2$ $S_3 = T_0/2$ $S_5 = T_1 + T_0/2$	$S_4 = T_0/2$ $S_6 = T_1+T_2+T_0/2$ $S_2 = T_2 + T_0/2$

IV.BLDC MOTOR

BLDC motors are used in industries such as Appliances, Automotive, Aerospace, Consumer, Medical, Industrial Automation Equipment and Instrumentation. As the name implies, BLDC motors do not use brushes for commutation; instead, they are electronically commutated. BLDC motors have many advantages over brushed DC motors and induction motors. A few of these are:

- Better speed versus torque characteristics
- High dynamic response
- Higher speed ranges
- Long operating life
- High efficiency
- Noiseless operation

In addition, the ratio of torque delivered to the size of the motor is higher, making it useful in applications where space and weight are critical factors.

A. Mathematical modelling of the BLDC motor

BLDC motor is fed by a three phase voltage source inverter as shown in Figure9.

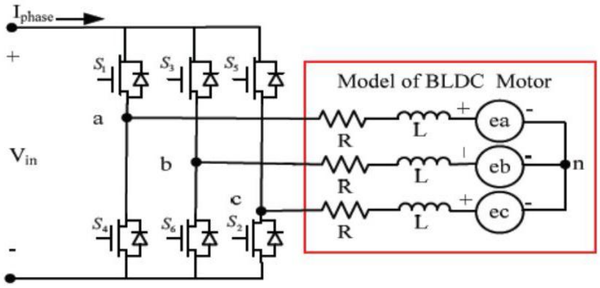

Fig.9: Configuration of BLDC motor drive system

The analysis of a BLDC motor is represented as the following equations:

$$V_a = Ri_a + (L\text{-}M)\frac{di_a}{dt} + e_a$$
$$V_b = Ri_b + (L\text{-}M)\frac{di_b}{dt} + e_b$$
$$V_c = Ri_c + (L\text{-}M)\frac{di_c}{dt} + e_c \quad (14)$$

Where V_a, V_b, V_c are the phase voltages, i_a, i_b, i_c are the phase currents, e_a, e_b, e_c are the phase back- EMF waveforms, R is the phase resistance, L is the phase inductance of each phase and M is the mutual inductance between any two phases.

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The electromagnetic torque is obtained as:

$$T_e = \frac{1}{\omega_r}\,(e_a i_a + e_b i_b + e_c i_c) \tag{15}$$

Where ω_r is the mechanical speed of the rotor and T_e is the electromagnetic torque. The equation of motion is:

$$\frac{d\omega_r}{dt} = \frac{1}{j}\,(T_e - T_L - B\,\omega_r) \tag{16}$$

B is the damping constant, J is the moment of inertia of the drive and T_L is the load torque. The electrical frequency related to the mechanical speed for a motor with P number of pole pairs:

$$\omega_e = P\,\omega_r \tag{17}$$

The rotor angle θ_r is: $$\theta_r = \int \omega_e\, dt \tag{18}$$

The instantaneous induced EMFs can be written as given in equation:

$$e_a = \sin(\theta_r)\, K_b\, \omega_m$$
$$e_b = \sin\left(\theta_r - \frac{2\pi}{3}\right) K_b\, \omega_m$$
$$e_c = \sin\left(\theta_r + \frac{2\pi}{3}\right) K_b\, \omega_m \tag{19}$$

Where, ω_m is the rotor mechanical speed and θ_r is the rotor electrical position. From the above equations, BLDC motor can be modelled.

V.SIMULATION OF SVPWM INVERTER FED PM BLDC MOTOR DRIVE

SVPWM inverter fed PM BLDC motor drive was designed & simulated successfully using MATLAB (SIMULINK) & following results were generated. Simulation parameters are given in Table 4.

Table 3: Simulation Parameters

DC voltage	240 V	L_s	0.00272 H
Fundamental frequency	50 Hz	J	0.0002 kg.m^2
Switching frequency	10 kHz	B	0.002N.m.s.rad^{-1}
R_s	0.7 Ω	K_b	0.5128V/rad/sec

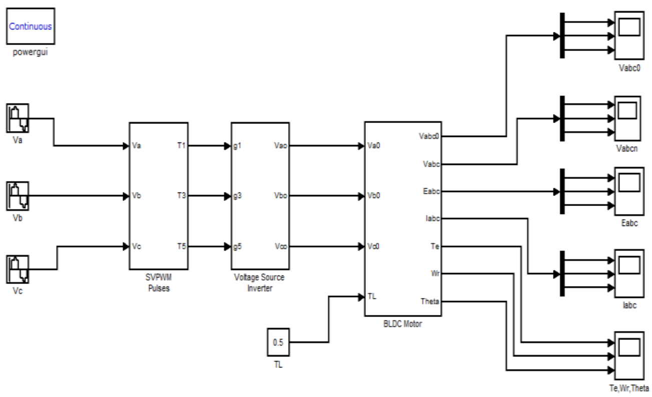

Fig.10: Simulink model of SVPWM Inverter fed PM BLDC motor drive

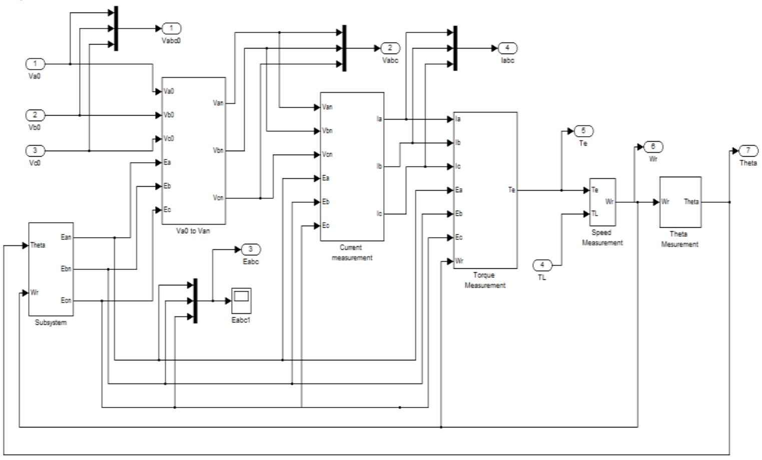

Fig.11: Simulink model of PM BLDC motor

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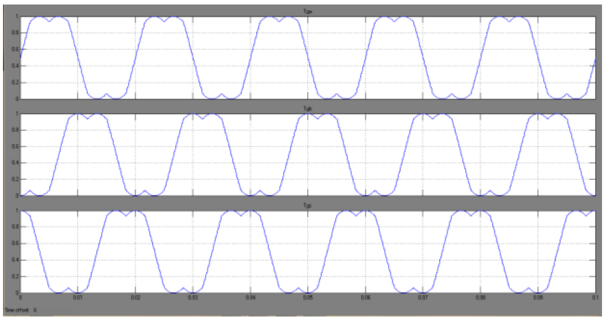
Fig.12: Reference voltage waveform of SVPWM

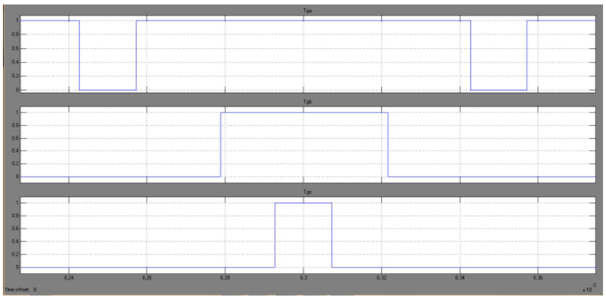
Fig.13: Switching pulses of T_1,T_3 & T_5 in Sector 1

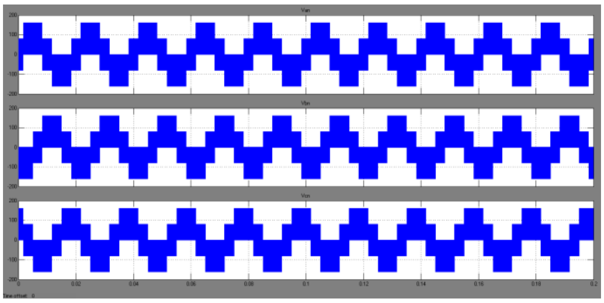
Fig.14: Motor Output Voltage waveforms

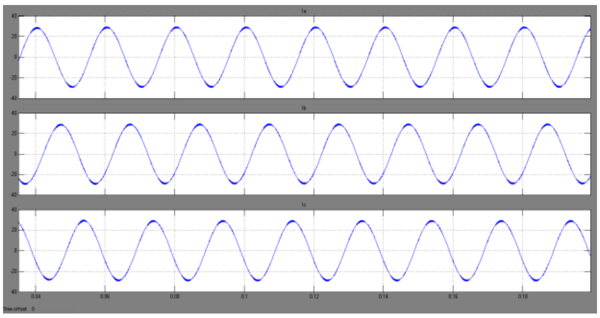
Fig.15: Motor Current waveforms

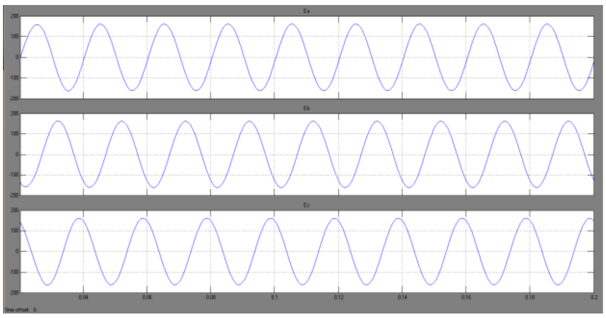
Fig.16: Sinusoidal back-emf waveforms

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VI. ADVANTAGES OF SVPWM COMPARED TO SINUSOIDAL PWM

1. Since the triplen order harmonics are appeared in the phase-to-centre voltage of SVPWM, it has higher modulation index compared to the Sinusoidal PWM. When the modulation index increases the THD of the output voltage decreases. Hence SVPWM has less amount of current and torque harmonics than those of sinusoidal PWM.
2. For Sinusoidal PWM (SPWM) $V_{max} = V_{dc}/2$
   For Space Vector PWM $V_{max} = V_{dc}/\sqrt{3}$
   Where, V_{dc} is DC-Link voltage. From this it is clear that Space Vector PWM can produce about 15 percent higher than Sinusoidal PWM in output voltage.
3. In SPWM different phases may switch simultaneously. But in SVPWM only one phase is switch at a time. Hence SVPWM has reduced switching losses compared to SPWM.
4. The SPWM inverter can be thought of as three separate driver stages which create each phase waveform independently. But Space Vector Modulation treats the inverter as a single unit.

VI.CONCLUSION

Space vector Modulation Technique has become the most popular and important PWM technique for Three Phase Voltage Source Inverters for the control of AC Induction, Brushless DC, Switched Reluctance and Permanent Magnet Synchronous Motors. In this paper analysis and simulation of space vector pulse width modulation is presented. The Modulation Index is higher for SVPWM as compared to SPWM. The current and torque harmonics produced are much less in case of SVPWM. In case of SVPWM the output voltage is about 15% more as compared to SPWM. The SVPWM technique utilizes DC bus voltage more efficiently and generates less harmonic distortion in a three-phase voltage-source inverter. SVPWM is very easy to implement. There are modern digital signal processors (DSP) with dedicated pins which give a pulse width modulated waveforms using SVM.

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